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Prediction of Two-Phase Pressure Drop and Void Fraction in Microchannels Using Probabilistic Flow Regime Mapping

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Abstract

Probabilistic two-phase flow map pressure drop and void fraction models are developed for 6-port microchannels in order to provide a more accurate and common means of predicting void fraction and pressure drop. The models are developed for R134a, R410A, and air-water in 6-port microchannels at 10° C saturation temperatures, qualities from 0 to 1, and mass fluxes varying from 50 to 300kg/m²-s. The probabilistic flow map models developed are found to accurately predict void fraction and pressure drop for the entire quality range and for all three fluids.

Key words: Two-phase flow; Microchannels; Pressure drop; Void fraction; Probabilistic mapping

Nomenclature

A	cross sectional area of the microchannel flow
a	curve fit constant
b	curve fit constant
c	curve fit constant
D_h	hydraulic diameter
d	curve fit constant
dP	pressure drop
dz	unit length
F	observed time fraction
f_D	Darcy friction factor
f_{vo}	vapor only friction factor
G	mass flux
g	curve fit constant
KE_{Avg}	average kinetic energy of the flow
P	microchannel wetted perimeter
Re_h	Reynolds number based on the hydraulic diameter
We_v	Weber number for vapor
X_{tt}	Lockhart-Martinelli parameter
X_{ann}	defined by equation 12
x	flow quality

Greek symbols

α	void fraction
ρ	density
$\rho_{2\phi}$	two-phase density
σ	surface tension
μ	dynamic viscosity
Φ_{vo}^2	vapor only two-phase multiplier

Subscripts

l	liquid
liq	pertaining to the liquid flow regime
int	pertaining to the intermittent flow regime
v	vapor
vap	pertaining to the vapor flow regime
ann	pertaining to the annular flow regime

1. Introduction

Numerous two-phase pressure drop and void fraction models have been developed for microchannels. Each model is developed using assumptions of the physics of the flow, which are accurate for a specific flow regime. However, models that accurately predict pressure drop and void fraction for all flow regimes without discontinuities could not be found in the literature.

In this paper new probabilistic two-phase flow map models are developed in order to predict pressure drop and void fraction for a wide range of qualities and mass fluxes where different flow regimes exist. Curve fits were made for flow regime time fractions for R410A, R134a, and air-water at mass fluxes of 50, 100, 200, and 300

kg/m²-s for qualities from 0 to 1 in the liquid, intermittent, vapor, and annular flow regimes. The most accurate pressure drop and void fraction models for each flow regime were identified for microchannels. The total pressure drop and void fraction is predicted as the sum of the flow regime time fractions multiplied by the corresponding best-suited model for that flow regime. In this way accurate models for the prediction of both pressure drop and void fraction in microchannels are developed, which incorporate flow regime information in a full range of qualities and mass fluxes.

2. Literature Review

2.1 Two-phase flow mapping

Garimella [1], Garimella et al. [2], Coleman and Garimella [3], El Hajal et al. [4], Thome et al. [5], Didi et al. [6], Zurcher et al. [7][8], Mandhane et al. [9], and Baker [10] have all described the importance of using flow pattern information in the determination of accurate two-phase flow models. Consequently, much attention has been directed towards developing two-phase flow regime maps. There are three main types of two-phase flow maps in the literature: Baker/Mandhane type, Taitel-Dukler type, and Steiner type. Baker [10] developed one of the first two-phase flow regime maps with air-water and air-oil data in large tubes. Baker [10] used superficial vapor mass flux times a fluid property scaling factor on the vertical axes and superficial liquid mass flux times a different fluid property scaling factor on the horizontal axis. Mandhane et al. [9] later developed a similar map with air water data, but used superficial gas and liquid velocities on the horizontal and vertical axes respectively. Dobson and Chato [11] then made modifications to the flow map of Mandhane et al. [9] by multiplying the axis by the square root of the vapor to air density ratio. Taitel-Dukler [12] developed a mechanistic type flow map with the Lockhart-Martinelli parameter on the horizontal axis and a modified Froude rate times a transition criteria on the vertical axis. Most of the recent two-phase flow regime maps found in the literature are Steiner type flow maps of the form found in Coleman and Garimella [3] as seen in Fig. 1. Garimella [1], Garimella et al. [2], El Hajal et al. [4], Thome et al. [5], and Didi et al. [6] all use similar Steiner style flow maps with quality on the horizontal axis and mass flux on the vertical axis. Some, like Chung and Kawaji [13] use the average flow velocity in the microchannel instead of mass flux on the vertical axis. All three types of flow maps indicate a particular flow regime at any given flow condition with lines dividing the transitions. This seems to lack a physical basis as Coleman and Garimella [3] and El Hajal et al. [4] indicate that more than one flow regime seems to exist near the boundaries. This poses a problem when attempting to develop pressure drop, void fraction, and heat transfer models that incorporate all flow regimes without having discontinuities at the boundaries. In addition, it is very difficult to implement this type of flow map into a model because the flow map cannot readily be represented by continuous functions for all quality ranges. The presence of more than one flow regime at the flow map boundaries seems to indicate that a probabilistic representation of the flow regimes may be better suited in describing the flow.

Niño et al. [14] presented two-phase flow mapping in microchannels in a distinctly different manner than found in the rest of the literature indicated above. Instead of definitively categorizing the flow regime at a given mass flux and quality, they recorded the time fraction in which each flow regime was observed in each channel at a given mass flux and quality. This was accomplished by obtaining numerous pictures of a given mass flux and quality at evenly spaced time intervals. This probabilistic flow mapping technique is especially important for

microchannels where each channel may simultaneously exhibit different flow regimes as can be seen in the flow visualization picture in Fig. 2. From Fig. 2 it can be seen that some of the channels are in the annular flow regime and others are seen to be in an intermittent flow regime. Moreover, the flow regime is seen to differ in the same channel at a given flow condition depending on the location of the observation. Figs. 3 through 14 show probabilistic flow maps with data obtained from Niño et al. [14]. From these figures it can be seen that the total time fraction of all flow regimes present add up to 1. Furthermore, the transitions between flow regimes are smooth. However, no functions were developed for describing the time fraction data nor was the data incorporated in any flow regime models.

2.2 Two-phase pressure drop models:

Numerous semi-empirical two-phase pressure drop models have been developed based on assumptions of the nature of the two-phase flow as a whole: homogeneous models and stratified models. Homogeneous flow models assume that the liquid and vapor phases form a homogeneous mixture with the same velocities, whereas the separated flow models assume that the liquid and vapor phases are separate with different velocities. Homogeneous two-phase pressure drop models have been developed for circular tubes such as the one presented by McAdams [15], Martinelli and Nelson [16], Lockhart and Martinelli [17], Friedel [18], Jung and Radermacher [19], Souza et al. [20], Yang and Webb [21], and Zhang and Kwon [22], and Niño et al. [14] all presented separated flow models which assume two-phase annular flow in tubes. Martinelli and Nelson [16] develop two-phase multipliers to relate the two-phase pressure drop to equivalent flow single-phase pressure drop. Lockhart and Martinelli [17] then correlated the two-phase liquid-only multiplier with the Lockhart-Martinelli parameter, which is the ratio of the frictional pressure drop of the two-phase flow to the frictional pressure drop of the liquid-only flow. However, the Lockhart-Martinelli parameter tends to infinity in an unphysical manner as the quality approaches zero. Friedel [18] utilized the Froude number (ratio of inertial to gravitational forces) and Weber number (ratio of inertial to surface tension forces) to correlate the two-phase liquid only multiplier to round tube data. Jung and Radermacher [19] used the Lockhart-Martinelli parameter in their expression for the two-phase liquid only multiplier in order to correlate their tube refrigerant flow boiling data. Souza et al. [20] utilized both the Lockhart-Martinelli parameter and the Froude number to correlate their data to a two-phase liquid only multiplier. Yang and Webb [21] developed a two-phase pressure drop model, which uses an equivalent single-phase liquid mass flux to correlate R-12 data in microchannels. Zhang and Kwon [22] use a two-phase liquid only multiplier that contains a reduced pressure term in order to correlate refrigerant data in tubes and microchannels. Recently, Niño et al. [14] developed a two-phase annular flow pressure drop model for microchannels, which is based on the work of Lockhart and Martinelli [17] and Martinelli and Nelson [16].

Both the homogeneous and separated flow type models are often used in all ranges of qualities and mass fluxes, some of which the assumptions of the physics of the flow do not apply. Recently, some of the literature, such as Didi et al. [6], seek to determine which existing pressure drop model is most accurate for a given flow regime. However, Garimella [1], Garimella et al. [2], and Chung and Kawaji [13] have developed and presented similar flow regime based pressure drop models of the intermittent two-phase flow regime in microchannels, which attempt to incorporate the physics of the flow into the model. These models require the use of a flow regime map to

determine the flow regime that exists and require flow visualization data on the slug rate. Flow regime based pressure drop models that incorporate flow visualization information in order to apply the correct physics for full ranges of qualities and mass fluxes were not found in the literature.

2.3 Two-phase void fraction models:

Like flow regime based pressure drop modeling, flow regime based modeling of void fraction is in its infancy stage. Numerous semi-empirical two-phase void fraction models have been developed using homogeneous or stratified flow assumptions. The homogeneous two-phase flow void fraction model assumes that the liquid and vapor densities travel at the same velocity. Lockhart and Martinelli [17], Levy [23], Zivi [24], Baroczy [25], Smith [26], Wallis [27], Premoli et al. [28], Domanski and Didion [29], Ahrens [30], and Bao et al. [31], have all presented void fraction models assuming stratified annular flow in tubes. Yashar et al. [32] developed a simple semi-empirical void fraction model that incorporates the Lockhart-Martinelli parameter and the “Froude Rate”, a parameter developed by Hurlburt and Newell [33]. This model was found to predict void fraction over a large range of conditions. Niño et al. [14] recently developed a semi-empirical two-phase void fraction model assuming annular flow in microchannels, and utilizes the Weber number and Lockhart-Martinelli parameter to correlate the data. Harms et al. [34] developed a mechanistic void fraction model for annular flow in horizontal tubes. However, the above void fraction models are typically used in all ranges of qualities and mass fluxes, some of which the assumptions of the physics of the flow do not apply. Flow regime based void fraction models that incorporate flow visualization information in order to apply the correct physics for full ranges of qualities and mass fluxes were not found in the literature.

3. Curve fitting of flow regime time fractions

Curve fits were made for the time fraction flow regime maps found in Niño et al. [14] in order to create user friendly flow regime based pressure drop and void fraction models.

The proposed liquid time fraction curve fit is given in equation 1.

$$F_{liq} = (1 - x)^a \quad (1)$$

This curve fit contains the physical limits of the liquid time fraction with a time fraction of 1 at a quality of 0 and a time fraction of 0 at a quality of 1.

The proposed intermittent curve fit is given in equation 2.

$$F_{int} = (1 - x)^{(b*x^c)} - (1 - x)^{(d)} \quad (2)$$

Equation 2 also contains the physical limits of the intermittent time fraction with a time fraction of 0 at a quality of both 0 and 1.

In Niño et al. [14] there are vapor time fractions at unexpectedly low qualities such as $x=0.1$ for low mass fluxes. This low quality vapor is determined to be intermittent flow in the subsequent analysis.

The proposed high quality vapor curve fit is given in equation 3. The low quality vapor is subtracted from the total vapor time fraction observations in order to obtain the high quality vapor time fraction values.

$$F_{vap} = x^g \quad (3)$$

Equation 3 contains the physical limits of vapor time fraction with a time fraction of zero at a quality of 0 and a time fraction of 1 at a quality of 1.

The proposed annular curve fit is simply 1 minus the sum of all other flow regime time fractions as seen in equation 4. By definition the total time fraction of all flow regimes must be identically equal to 1.

$$F_{ann} = 1 - F_{liq} - F_{int} - F_{vap} \quad (4)$$

Time fraction curve fits are plotted for R410A at 10°C and a mass fluxes of 50, 100, 200, and 300 kg/m²-s in Figs. 3 through 6 respectively, for R134a at 10°C and a mass fluxes of 50, 100, 200, and 300 kg/m²-s in Figs. 7 through 10 respectively, for air-water at 20°C and a mass fluxes of 50, 100, 200, and 300 kg/m²-s in Figs. 11 through 14 respectively along with the time fraction data found in Niño et al. [14] for 1.54mm hydraulic diameter 6-port microchannels. From these figures it can be seen that the curve fits reasonably represent the data. The curve fit constants for the above curve fits of R410A, R134a, and air-water are tabulated in tables 1a, 1b, and 1c, respectively.

4. Probabilistic pressure drop modeling

With the time fraction curve fit functions and curve fit constants established, a probabilistic flow regime pressure drop model can be developed for practical use. Pressure drop can be predicted by simply summing the time fraction of a flow regime multiplied by the best suited pressure drop model for the respective flow regime as shown in equation 5.

$$\left(\frac{dP}{dz}\right)_{total} = F_{liq} \left(\frac{dP}{dz}\right)_{liq} + F_{int} \left(\frac{dP}{dz}\right)_{int} + F_{vap} \left(\frac{dP}{dz}\right)_{vap} + F_{ann} \left(\frac{dP}{dz}\right)_{ann} \quad (5)$$

Consequently, this model applies the appropriate assumptions for a full range of flow conditions. The pressure drop models used for each flow regime are the best pressure drop models identified for microchannels as described in Niño et al. [14]. The Reynolds number for the microchannels is defined according to Niño et al. [14] work as shown in equation 6.

$$Re_h = \frac{GD_h}{\mu} \quad \text{where } D_h = \frac{4A}{P} \quad (6)$$

4.1 Liquid flow pressure drop model

By solving the Navier-Stokes equation the Darcy friction factor used for single phase flow in the laminar regime, $Re_h < 2,300$ is given in equation 7.

$$f_D = \frac{64}{Re_h} \quad (7)$$

The Darcy friction factor used for turbulent flow, $Re_h > 2,300$, is given by equation 8 (Blasius Equation).

$$f_D = \frac{0.3164}{Re_h^{0.25}} \quad (8)$$

The liquid pressure drop is then determined using equation 9.

$$\frac{dP}{dz} = f_D \left(\frac{1}{D_h} \right) \frac{G^2}{2\rho} \quad (9)$$

These relations were found to best model single-phase pressure drop for microchannels in Niño et al. [14].

4.2 Vapor flow pressure drop model

The vapor pressure drop model is exactly the same as the model used for liquid flow (equations 7 through 9) since vapor flow is also a single-phase flow.

4.3 Intermittent flow pressure drop model

The intermittent flow pressure drop model developed in Niño et al. [14] is given in equation 10 below. This model assumes homogeneous flow parameters and uses the two-phase mixture's average kinetic energy to predict pressure drop.

$$\left(\frac{\Delta P}{\Delta z} \right)_{\text{int}} = 0.045 \frac{1}{D_h} KE_{\text{Avg}} \quad \text{where} \quad KE_{\text{Avg}} = \frac{G^2}{2\rho_{2\phi}} \quad \text{and} \quad \rho_{2\phi} = \left[\frac{x}{\rho_v} + \frac{(1-x)}{\rho_l} \right]^{-1} \quad (10)$$

Niño et al. [14] found that equation 10 accurately predicts intermittent flow pressure drop in microchannels for air-water, R410A, and R134a. Adams et al. [35] found equation (10) to be valid for R245fa, carbon dioxide, and ammonia in microchannels.

4.4 Annular flow (separated flow) pressure drop model

The annular flow pressure drop model used, developed in Niño et al. [14], is given by the following relationship in equation 11.

$$\left(\frac{dP}{dz} \right)_{2\phi} = \Phi_{vo}^2 \left(\frac{dP}{dz} \right)_{vo} \quad (11)$$

Where Φ_{vo}^2 is an experimentally determined two-phase multiplier given by equation 12 (obtained from Niño et al. [36]).

$$\Phi_{vo}^2 = \exp(-0.046 X_{\text{ann}}) + 0.22[\exp(-0.002 X_{\text{ann}}) - \exp(-7 X_{\text{ann}})]$$

$$\text{Where } X_{\text{ann}} = \left[\left(X_{tt} + \frac{1}{We_v^{1.3}} \right) \left(\frac{\rho_l}{\rho_v} \right)^{0.9} \right], \quad We_v = \frac{\left[\frac{(xG)^2}{\rho_v} \right]}{\frac{\sigma}{D_h}}, \text{ and}$$

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.875} \left(\frac{\rho_v}{\rho_l} \right)^{0.5} \left(\frac{\mu_l}{\mu_v} \right)^{0.125} \quad (12)$$

Furthermore, the vapor only pressure drop is determined by equation 13 below.

$$\left(\frac{dP}{dz} \right)_{vo} = 2f_{vo} \frac{1}{D_h} \frac{G^2}{\rho_v} \quad (13)$$

4.5 Treatment of low quality vapor

The existence of low quality vapor at qualities of 0.3 and less in Niño et al. [14] is unexpected. Vapor flow is normally associated with high quality flow. It is hypothesized, that the flow classified as low quality vapor in the work of Niño et al. [14] may actually be intermittent flow with very long bubbles that are longer than the field of view of the camera. In order to test this hypothesis, the pressure drop model given in equation 5 was implemented twice: first treating low quality vapor as vapor, and second treating the low quality vapor as intermittent flow. Treatment of low quality vapor as vapor predicted a significantly higher pressure drop than experimentally obtained at low quality ranges. However, when the low quality vapor was treated as intermittent flow the model was found to represent the data very well. This leads one to believe that the low quality vapor observations found in the work of Niño et al. [14] are in fact intermittent flow. Consequently, the low quality vapor time fraction functions are assumed to be intermittent flow time fractions in the analysis.

4.6 Evaluation of the probabilistic pressure drop model

Using equation 5, along with curve fit equations 1 through 4 and pressure drop model equations 6 through 13, pressure drop is predicted for R410A, R134a, and air-water for a range of mass fluxes and qualities. The predicted pressure drop determined by the probabilistic model and the measured pressure drop is plotted for R410A, and R134a at 10° C with a range of mass fluxes and qualities in Figs. 15 and 16 respectively. The experimental pressure drop data was obtained from Niño et al. [14]. From Figs. 15 and 16 it can be seen that the data lies very close to the model lines for all mass fluxes and qualities investigated. Furthermore, it can be seen that the probabilistic model has the correct limits. The predicted pressure drop determined by the probabilistic model and the pressure drop data obtained from Niño et al. [14] is plotted for air-water at 20° C for a range of mass fluxes and qualities in Fig. 17. From this figure it can be seen that the pressure drop data lie very close to the probabilistic model line. The probabilistic model curves are not smooth due to differences in the air supply pressure for the various flow conditions. The air pressure variations resulted in different vapor densities from point to point, so the probabilistic model pressure drop was determined for each point using the actual vapor density found at that data point. A constant vapor density was assumed in the high quality regions where the experimental data were not available in order to show the high quality range trends. The problem associated with varying vapor densities does not exist with the refrigerant data because the vapor density is a function of the saturation temperature. In the air-water experiments the vapor density is almost entirely a function of the air pressure and temperature supplied because the partial pressure of the water vapor is minimal. It should be noted from the above figures that the probabilistic model curves bend in a complex fashion based upon the physical reality of the flow field. Moreover, the probabilistic pressure drop model developed reflects the actual trends in the experimental data.

In order to further illustrate the accuracy of the probabilistic flow map model it is compared with the pressure drop data found in Niño et al. [14] for 6-port microchannels and with several other pressure drop models in Fig. 18. From this figure it can be seen that the probabilistic flow map model best represents the data for most quality ranges as it is seen to have essentially the same trends as the data with physically correct limits as the quality approaches zero or one. The Jung and Radermacher [19], and Sousa et al. (1993) models approach zero as the quality approaches 1, which lack physical significance because they both contain a $(1-x)$ term in the numerator of their two-phase multiplier expressions. The Yang and Webb (1996) model also lacks a physically correct pressure

drop, because the pressure drop is much higher than vapor only pressure drop as the quality approaches 1. The probabilistic model pressure drop predictions versus the measured pressure drop values are plotted in Fig. 19 for R410A, R134a, and air-water. From Fig. 19 it can be seen that the model error mostly lies within 20 % error lines. The percentage of predicted values that lie within 20% error lines are tabulated in Table 2 in order to further compare the accuracy of the probabilistic model with the correlations found in Fig. 18. It is evident from Table 2 that the probabilistic model performs better than the rest of the models except for air-water pressure drop with the McAdams (1954) model performing equally well.

5. Probabilistic void fraction modeling

Probabilistic flow regime map based modeling can be applied to void fraction as well. Similar to pressure drop, void fraction can be modeled by simply summing the time fraction of a flow regime multiplied by the best suited void fraction model available for the respective flow regime as shown in equation 14 below.

$$\alpha_{total} = F_{liq} \alpha_{liq} + F_{int} \alpha_{int} + F_{vap} \alpha_{vap} + F_{ann} \alpha_{ann} \quad (14)$$

5.1 Liquid and vapor void fraction model

By definition, the liquid only flow void fraction is identically equal to 0, and the vapor only flow void fraction is identically equal to 1.

5.2 Intermittent flow void fraction

The intermittent flow void fraction model assumes a homogenous flow where the liquid and vapor are flowing at the same velocity. Therefore, the equation given for intermittent flow void fraction is given by equation 15 below.

$$\alpha_{int} = \frac{1}{1 + \frac{1-x}{x} \left(\frac{\rho_v}{\rho_l} \right)} \quad (15)$$

5.3 Annular flow void fraction

The annular flow void fraction model used in the probabilistic model utilizes the Weber number and the Lockhart Martilelli parameter, just as modeled in the pressure drop model for annular flow. The equation for the annular flow void fraction model, developed by Niño et al. [14], is given in equation 16 below.

$$\alpha_{ann} = \left[1 + \left(X_{tt} + \frac{1}{We_v^{1.3}} \right) \left(\frac{\rho_l}{\rho_v} \right)^{0.9} \right]^{-0.06} \quad \text{where } X_{tt}, \text{ and } We_v \text{ are defined}$$

in equation 12 above

(16)

5.4 Evaluation of the probabilistic void fraction model

Using equation 14, along with curve fit equations 1 through 4 and void fraction model equations 15 and 16, void fraction is predicted for R410A, R134a, and air-water for a range of mass fluxes and qualities. The probabilistic void fraction model and void fraction data are plotted for R410A and R134a at 10° C for a range of mass fluxes and qualities in Figs. 20 and 21, respectively. In addition, the probabilistic void fraction model and void fraction data are plotted for air-water at 20° C in Fig. 22. The void fraction data was obtained from Niño et al. [14].

From Figs. 20 through 22 it can be seen that the data lies close to the probabilistic model curves for the range of qualities and mass fluxes investigated. The deviation from the model can partly be attributed to the large error associated with the void fraction measurements. Like the developed probabilistic pressure drop model, the developed probabilistic void fraction model contains inflection points with physical significance associated with the inflections. The inflections seem to signify a flow regime change. Fig. 23 compares the probabilistic flow regime map based void fraction model with other models.

6. Conclusion

Many pressure drop and void fraction models can be found in the literature, however the assumptions which they use tend to only apply to a particular flow regime. Probabilistic two-phase flow regime maps are found to be a suitable flow maps for incorporating flow regime information into pressure drop and void fraction models. Curve fits were developed for liquid, intermittent, annular, and vapor flow regime time fractions for R410A, R134a, and air-water probabilistic flow regime maps for 6-port microchannels. These curve fit functions capture the time fraction physical limits. Probabilistic pressure drop and void fraction models based on the time fraction curve fits of the two-phase flow were developed. This method is unique in that the flow is modeled based on the actual physical flow field characteristics, which allows the incorporation of the appropriate weighting of the respective two-phase flow models. It was found that the probabilistic flow regime map based pressure drop model predicts pressure drop very well. Moreover, the probabilistic flow mapping based void fraction model predicts void fraction close to the data. However, more accurate void fraction data must be obtained in order to further evaluate the probabilistic flow mapping based void fraction model. Consequently, the probabilistic flow mapping based modeling technique proves to be a powerful tool in predicting pressure drop and void fraction in microchannels.

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